INTRODUCTION

Rogers, Tinsley, and Borcherdt (1985) described an empirical technique for predicting relative site response by comparing ground motion spectra in three period bands (total period band is from 0.2 to 10 seconds) relative to the thickness and the physical properties of the earth materials which lie beneath the instrument sites. A set of three-component recordings of Nevada Test Site nuclear tests and a compilation of geologic attributes at each site comprise the set of basic data employed in the analysis. A suite of site types (clusters) is defined statistically in terms of common geologic attributes. The attributes defining each cluster are those attributes that most strongly correlate with, or influence, site response in a given period band. Maps showing the distribution of these geologic attributes are prepared as overlays and are used to construct derivative maps which, in turn, depict relative site response for part of the Los Angeles area.

Future research is desirable, both to explore further the methodology and to test the predictions of the model compared to patterns of damage caused by historical earthquakes, as well as applying the technique to basins other than the Los Angeles region. The principal goal of these and related studies is to develop microzonation technology so that sites which are especially at risk can be identified and appropriate measures can be adopted to reduce significantly losses of life and property.

VARIABLE GROUND RESPONSE IN THE LOS ANGELES REGION

Local geologic conditions long have been recognized as a significant factor influencing ground shaking (Kanai, 1952; Gutenberg, 1957; Medvedev, 1962), although the quantitative prediction of site effects using either empirical or theoretical models is still developmental. We have extended to the Los Angeles area the technique developed by Borcherdt and Gibbs (1976), recasting the technique to include the effects of near-surface site properties and geologic structure. To determine relations among local geologic factors and site response, 19 nuclear explosions were recorded at 98 sites throughout the Los Angeles region (Rogers and others, 1980). Sites were selected to obtain as complete a sample of underlying geologic conditions and as broad a geographic coverage as possible. The seismic source (Nevada Test Site) lies some 400 to 450 km from the recording sites; effects of azimuthal variations in the radiated energy are similar for all sites. Each site's response characteristics over the period band 0.2 to 10 seconds was
estimated by computing Fourier spectra and alluvium-to-crystalline rock spectral ratios (Rogers and others, 1980). The site CIT, underlain by crystalline rock, was instrumented for every nuclear explosion and was the rock site against which recordings measured at all other sites were compared (see figure 1A).

Distant nuclear explosions generate ground motion records in which the effects of site conditions are readily apparent. Figure 1A shows time histories recorded simultaneously at eight sites from a single Nevada Test Site nuclear explosion. This example illustrates several effects of local site conditions that are observed commonly in recorded time histories when the source of shaking is distant. Maximum amplitudes of motion recorded on the alluvial sites are several times larger than those recorded on the sedimentary and crystalline rock sites. The degree of amplification occurring in the long-period peak amplitudes visible in these records is greatest at sites underlain by the thickest sediments (HOL: 300 m; MIL: 370 m; ATH: 370 m; GMB: 120 m; FS4: 15 m).

The amplitude spectral ratios computed for the simultaneous recordings shown in figure 1A are presented in figure 1B. These ratios show that the effects of site conditions relative to those at CIT are strongly frequency dependent, and amplification occurs for many of the sites over most of the frequency band for which the signal-to-noise ratio is favorable (Rogers and others, 1980). Amplification factors of the horizontal component of ground motions range from 2 to 7 at frequencies less than 1 Hz for those sites on thick sections of alluvium; lower amplification factors are found at these frequencies for the site FS4 underlain by a thin alluvial section. Considerable amplification at intermediate frequencies (1-2 Hz) and at higher frequencies (2-5 Hz) occurs at several sites, notably FS4, where a prominent ground resonant frequency is observed. Resonance is not apparent for thick alluvial sites (spectra are relatively flat across the entire observed frequency range). Spectral ratios at site GOC suggest that the response of the two crystalline rock sites (GOC, CIT) is similar at lower frequencies, but at intermediate and high frequencies, ground motions at GOC are higher than at CIT. Relative to CIT, site 3838, located on sedimentary rock, shows a uniformly greater response than GOC, but a lesser response than the sites underlain by thick alluvial sections.

COMPARISON OF GEOLOGIC FACTORS AND GROUND RESPONSE

Geologic parameters were chosen to characterize the recording sites because either the parameters have some direct application in a theoretical model of site response or, in past studies, the parameters have been reported to have some influence on ground shaking. Parameters such as percent (silt+clay) and depth to water table have been reported to influence site response, whereas shear-wave velocity (or void ratio, which strongly influences the shear modulus), thickness of Holocene deposits, thickness of Quaternary deposits, and depth to crystalline basement rocks are parameters that might be used directly to model site response. Most of these data are available in the literature or are obtainable from published geologic maps, records of water wells, and geotechnical studies conducted for engineering purposes; these data are of especially great value if they can also be used to estimate site response in some quantitative manner.
Figure 1A. Radial component time histories recorded simultaneously at 8 sites, grouped according to the type of geologic materials immediately beneath each recording station.

Figure 1B. Spectral ratios of the radial components of ground motion shown in figure 1A, relative to station CIT, a crystalline rock site.
We examined the relation between site response and the geologic parameters by grouping the sites according to variations in one of the geologic factors and then computing mean response for each group. The following ground response characteristics emerged:

- Sites underlain by Holocene and Pleistocene sediments undergo levels of shaking 2.6 to 3.4 times greater than those sites underlain by crystalline rocks, for all period bands,

- The void ratio of near-surface deposits has a strong influence on short-period response, with void ratios in the 0.8-0.9 range indicating a mean response on soil six times greater than on crystalline rock and three times greater than on low-void-ratio soils, and

- Amplitudes in the long-period band (3-10 seconds) generally increase with increasing thickness of Quaternary deposits and/or depth to crystalline basement rocks.

Additional detailed studies of the influence of all geologic parameters were conducted using data analysis and regression techniques (Mosteller and Tukey, 1977). These studies indicate that the most pronounced changes in site response were correlated with changes in void ratio, thickness of Holocene deposits, depth to crystalline basement rocks, and thickness of Quaternary deposits.

CLUSTERING OF SITES BY GEOLOGIC ATTRIBUTES TO REFLECT VARIABILITY IN SHAKING RESPONSE

Sites that have similar response characteristics can be clustered (grouped) by computing an analytical measure of similarity among a list of items based on their attributes. In our analysis, the items are the recording sites and the attributes are the geologic properties of each site. We cannot use the response factor (amplification factor) as an attribute, because we are attempting to predict response as a function of the geologic properties of the site. The clustering algorithm (IMSL, 1982) is used to establish a hierarchy showing which items are most nearly alike, and also show the level within the hierarchy at which clusters of similar items are most alike.

Once this procedure is used to form clusters based on any chosen set of factors, discriminate analysis (Nie and others, 1975) is used to determine the degree to which these factors define unique clusters; the significance of each factor's discriminating power is computed based on the statistical relations among factors within and between the respective clusters. One can calculate the probability that any single member of a cluster belongs to that cluster or to any other cluster; based on these probabilities, the percentage of sites that have been correctly classified can be calculated. In our study, the cluster sets that were selected were those having the lowest dispersion in the defining variables while incorporating only those factors having the most pronounced effect in a given
period band. The final sets of clusters are a compromise between the many
clusters required to preserve the complexity in site response as a function of
geology, and the requirement that each cluster contain enough cases to impart
statistical validity to the estimate of the average response for the cluster.

Two clusters for rock sites and eight clusters for alluvial sites were derived
for the short-period band (0.2-0.5 sec) and the respective attributes of each cluster
are shown in figure 2. To understand figure 2, an example may be helpful. Cluster
4A includes sites that have a depth to crystalline basement rocks of greater than
0.5 km, a thickness of Holocene deposits that is greater than 20 m, void ratios in
the range of 0.6-0.7, and a geometric mean response of about 3.6, relative to
crystalline rock sites. Moreover, if an attribute such as Holocene thickness is held
fixed, response increases as void ratio increases (compare clusters 1A, 3A, and 6A).
Response also increases, for a constant void ratio, as the thickness of Holocene
deposits increases and passes through a critical range (compare clusters 6A, 7A,
and 8A). Not surprisingly, rock sites 1R and 2R indicate a geometric mean
response that typically is less than that of the clusters of alluvial sites. A
comparison of clusters 1A and 2A shows that sites underlain by shallow alluvium
over crystalline rock (2A) have a response two times higher than does the same
type of site overlying a deep sedimentary basin, a relation that emphasized the
importance of a high impedance contrast at shallow depths as a factor in ground
response.

Although we have identified 10 clusters, with a moderate range in the
geologic and response factors in each cluster, it is useful to compare average
spectral level with shaking intensity. From Borcherdt and others (1975), if we
adopt the reasonable assumption that a factor of two in mean spectral level
corresponds to a change of one Modified Mercalli Intensity unit, then from the data
in figure 2, we can infer that the 10 clusters predict the true site-response more
closely than one intensity unit increment for 90 percent of the cases (the
geometric 90 percent confidence interval (1.45) is less than a factor of two).
Clusters also were derived for intermediate- and long-period bands on the basis of
Quaternary thickness and depth to crystalline basement rock (Rogers and others,
1985), but these clusters will not be discussed here.

Map Showing Predicted Site Response for a Portion of the Los Angeles Region

The response maps for the intermediate- and short-period bands for a small
area centered in the Los Angeles Civic Center are shown in figures 3A and 3B.
These figures are based on the clusters just discussed and on a set of maps
delineating the geographic distribution of the important geotechnical attributes
of each cluster.

The intermediate-period map (figure 3A), of significance to structures
between five and 30 stories high, predicts that low response will characterize areas
underlain by rock and thickness of alluvium of less than about 150 m; intermediate
levels of response will occur in areas where the thickness of alluvium is greater
than 150 m and/or where the depth to crystalline basement rock ranges between
0.15 and 4 km; highest levels of response will be observed in areas where depth to
basement rocks ranges from 4 to 6 km. Slightly lower levels of response are
predicted in the deepest parts of the Los Angeles basin. Lowest levels of response
Figure 2. Site clusters for short-period ground motions in the Los Angeles region. Solid dots indicate the mean of the short-period spectral ratios for a given cluster, mean void ratio, Holocene deposit thickness, and depth to crystalline basement rock groups, as appropriate. Vertical bars indicate the range in the variable for a given cluster, and side ticks indicate the 90% confidence intervals.
Figures 3A and 3B. Maps showing predicted relative shaking response for part of the Los Angeles Basin. Numbers are mean amplification factors, comparing levels of shaking to sites on crystalline basement rock. Fig. 3A is a map for intermediate periods (0.5-3.3 sec). Stippling outlines area of Figure 3B. Fig. 3B is the map for short-periods (0.2-0.5 seconds).
are predicted in the areas where crystalline basement is at or near the surface in the Santa Monica Mountains and the Verdugo Mountains.

The short-period map, which is most relevant for buildings in the two- to five-story class, has been prepared for the central third of the area shown in the long-period map. The lowest response is predicted for areas underlain by crystalline and sedimentary rock, and the highest response will be observed in regions where thickness of near-surface alluvium (range 11 to 20 m) and high void ratio (exceeding 0.7) produces significant resonant response in this period band. This map rather closely approximates a surficial geologic map: details of alluvial valleys, including that of the Los Angeles River, are delineated. The southwest part of the map depicts an area where silty deposits (characterized by high void ratios) comprising parts of the recent floodplain of the Los Angeles River are widespread in the section and wedge out against the east flank of the Newport-Inglewood zone of deformation. There, Pleistocene deposits characterized by low void ratios are exposed. We note that high levels of short-period response may occur at rock sites if these sites are located near the crest of a ridge or other pronounced topographic convexity, as shown by the range of high response for clusters 1R and 2R (figure 3).

AVENUES FOR FUTURE RESEARCH

We anticipate that several avenues of inquiry seem to be especially important in analyzing the overall significance of the empirical approach used in our analysis of ground response in the Los Angeles region. In particular, testing of the methodology is essential, and an experiment that will be conducted in the near future will use data obtained following the March, 1985 Chilean earthquake. Digital recordings of aftershocks were made there at a suite of sites that are underlain by a wide variety of earth materials and geologic site conditions, in zones of high, intermediate, and low main-shock intensities, and at strong-motion main shock recording sites. The testing could proceed along several lines:

- What is the correlation between the change in Modified Mercalli Intensity level and aftershock (low strain) alluvium-to-rock mean spectral ratios? Preliminary results indicate a strong correlation exists between intensity change and the short-period (0.2-0.5 second) mean spectral ratios in the Santiago, Chile, area (Algermissen, 1985).

- How well do the short-period site clusters derived for the Los Angeles region (Rogers and others, 1985) predict geographic changes in intensity observed in Santiago, Chile? A strong correlation would demonstrate a broader applicability of the technique.

- Comparison of the mean site-response spectral values observed during the main shock and aftershocks in the Chilean earthquake would help support the validity of the numerical values of relative ground shaking predictions for strong motion conditions.
In our view, the methodology should also be expanded, both in an applied sphere and in a research sphere. We would apply the technique to a broader geographic region of the Los Angeles area; mapping of predicted ground response according to the clusters derived for the Los Angeles area but involving parts of the San Fernando Valley is in progress. Depending on the success of this endeavor, continuation of the work in other basins of southern California may be advisable. In the research sphere, we must collect additional data to permit improved estimates of the mean values and standard deviations for the respective clusters and add new clusters and perhaps redefine or regroup components of the existing clusters as necessary using new data from many regions. Further evaluation of the effects of site response relative to peak acceleration, velocity, and displacement parameters is needed, in order to translate the results of the study in terms which are more directly useful in engineering practice. The results could also be cast in terms of modifications to design spectra.

Microzonation maps should have potential applications for land-use planning purposes, where it may be desirable to avoid the siting of critical facilities and lifelines in zones of predicted high levels of shaking and siting of high-rise structures in zones of long-period intense shaking. In the latter case, it is particularly important to avoid the siting of high-rise structures having resonant period equal to or nearly equal to that of the predominant period of ground shaking of the site, as demonstrated by the 1985 Mexico earthquake and building damage to high-rise structures in Mexico City.

Where avoidance cannot be accomplished, special consideration (at least for critical structures) should be given to the design of these facilities when they are sited in zones of predicted high shaking intensity. For instance, it is possible to use design spectra that account for site conditions; or modify the design of buildings in order that the predominant period of the building does not coincide with the predominant period of ground shaking.

Microzonation maps have been and will continue to be important to studies of earthquake losses. Accurate estimates of future losses depend heavily on understanding the geographic variation in ground shaking. In turn, such studies are important elements of emergency preparedness and response.

In summary, application of ground shaking microzonation techniques to determine the nature of any increased risk owing to geologic site conditions should, over the long term, help to significantly reduce losses of life and property that stem from collapse of and structural damage to buildings.
REFERENCES


Kanai, K., 1952, Relation between the nature of surface layer and the amplitudes of earthquake motions: Bulletin of the Earthquake Research Institute, University of Tokyo, v. 30, pt. 1, p. 31-37.


